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Influence of Geometry and Flow Variations on NO Formation in the Quick Mixer of a Staged Combustor

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ABSTRACT

Staged combustion, such as Rich-Burn/Quick-Mix/Lean-Burn (RQL), is a viable strategy to meet nitric oxide (NO) emission goals for both stationary and propulsion gas turbine engines. A critical element of the design is the quick mixer section where the potential for NO production is high. While numerical calculations of the quick mixer under reacting conditions have been conducted, the hostile environment and lack of appropriate diagnostics have, to date, precluded experimental probing of the reacting case. As an alternative to understanding the effect of geometry and flow variations on the production of NO in the quick mixer, the present paper presents (1) a series of non-reacting parametric studies, and (2) a computational method to extrapolate the results of the non-reacting experiments to reacting conditions. The results show that the rate of NO production is highest in the immediate vicinity of the injection plane. For a given momentum flux ratio between the jets and mainstream, the most effective mixing geometry is that which mixes effectively in both (1) the plane of injection, and (2) the wall regions downstream of the plane of injection. The tailoring of the mixing is key to minimize the NO formed. As a result, the best overall mixer with respect to the minimization of NO production may depend on the system specific characteristics of the particular application.

NOMENCLATURE

J	jet to mainstream momentum ratio
ϕ	orifice angle with respect to mainstream
f	mixture fraction
MR	jet to mainstream mass ratio
DR	jet to mainstream density ratio
MOD1	eight-hole baseline geometry
MOD2	8:1 aspect ratio slanted slots, $\phi = 45°$
MOD5	4:1 aspect ratio slanted slots, $\phi = 45°$

INTRODUCTION

The reduction of nitric oxide (NO) from combustion sources is of interest in urban environments where NO participates in the production of photochemical oxidant, in the troposphere were NO participates in the balance of greenhouse gases, and in the stratosphere where NO can deplete the resident ozone. Gas turbines are unique as combustion sources that operate in each element. As a result, the gas turbine is a target of opportunity for the reduction of nitric oxide in both stationary and aeroengine operation.

An early strategy for the reduction of nitric oxide from stationary gas turbine engines is staged (e.g., Rich-Burn/Quick-Mix/Lean-Burn, RQL) combustion, developed and demonstrated in the late 1970's (Mosier and Pierce, 1980). In this concept, the primary zone operates rich. The products of combustion, high in carbon monoxide, enter a quick mixer to mix and react with the remaining air. The combustion is completed in the lean-burn zone.

A key to the success of the staged combustor is achieving a mixing pattern in the mixer that minimizes NO production. The transition of the bulk flow from rich to lean mixtures will inevitably form, albeit momentarily, near-stoichiometric mixtures.. Near-stoichiometric conditions produce the highest temperatures and create, as a result, the highest production of NO. As a result, mixing can affect (1) the mass of material that experiences near stoichiometric mixtures, and (2) the time that such material spends in residence at near-stoichiometric conditions. Mixing can also result in relatively high temperatures in the wall region which can locally degrade the combustor liner and further promote the formation of NO.

To ensure the success of the staged concept, it is important to understand the mixing behavior in the mixer, and the relationship of this behavior to the formation of NO.

To address this need, the goal of the present work focused on (1) developing an understanding of the mixing processes in the mixer section of a staged gas turbine combustor, and (2) gaining insight into the features of the mixer that govern the relationship of mixing to the production of NO. Presented are non-reacting experiments where results are extrapolated through modeling to the practical, reacting conditions of an actual staged combustor.

BACKGROUND

Mixing of jets in a confined cross flow has a variety of practical applications that have motivated a number of studies in recent decades. In a gas turbine combustor, for example, mixing of relatively cool air jets in the hot combustion products is employed to reduce temperatures to levels acceptable for the turbine. Mixing of jets in a cross flow is also important in applications such as the discharge of effluents into water and in the transition from hover to cruise of V/STOL aircraft.

The majority of the previous research of jets in a cross flow has been performed in rectangular geometries. The influence of orifice geometry and spacing, jet-to-mainstream momentum flux ratio (J), and density ratio (DR) has been summarized for single and double sided injection (e.g., Holdeman, 1993). As a result of these studies, momentum flux ratio, orifice geometry, and orifice spacing have been identified as the dominant parameters influencing the mixing pattern.

The renewed interest in low-NO emissions from gas turbine engines (e.g., Shaw, 1991) has added a new dimension to the study of jet mixing in a confined cross flow. Instead of simply focusing on overall performance of the mixer, the emphasis is now directed to the role of mixing on the formation of NO. As a result, whereas previous studies have addressed the uniformity of mixing at a selected downstream location, the requirement to reduce NO in the mixer necessitates a critical analysis of (1) the history of mixing from the point of injection, and (2) how this history affects the formation of NO.

Numerical studies have recently been conducted that address the formation of NO under reacting conditions in a quick mixer (Talpallikar, et al., 1991; Smith, Talpallikar, and Holdeman, 1991). The hostile environment of the mixer (i.e., reaction, high pressure, high temperature, and limited optical access) have, to date, precluded the in-situ measurements that are needed to understand the role of mixing on NO production. In addition, optical diagnostics are not to the level of maturity that is necessary to probe such hostile environments.

Recently, experiments have been conducted under non-reacting conditions to explore (1) the mixing of jets in a cross-flow, and (2) the role of geometry and flow variations in the mixer performance (Vranos, et al., 1991; Hatch, et al., 1995). The present study takes the next step. In particular, the present paper presents (1) a series of non-reacting parametric studies, (2) a computational method to extrapolate the results of the non-reacting experiments to reacting conditions, and (3) results that provide valuable insight into the relationship of NO performance to mixer geometry and operation.

EXPERIMENT

Following the lead from previous mixing studies, a series of parametric experiments were undertaken in the present study to determine the influence of jet-to-mainstream momentum flux ratio (J) and orifice geometry on (1) overall mixing, and (2) NO formation potential in a can geometry. The parametric experiments investigated a range of J values that include 25, 52, and 80. A jet-to-mainstream mass ratio (MR) of 2.2 was maintained at each tested J value. The momentum flux ratio range and the mass ratio were selected with reference to actual staged combustor conditions. An area discharge coefficient of 0.80 was assumed in designing the orifices.

The modules tested in the parametric studies were fabricated from 3-inch (76 mm) inside diameter, 0.125-inch (3.18 mm) thick Plexiglass tubing. Plexiglass was selected for its optical quality, and ease of fabrication. For each value of J, configurations with eight, equally spaced orifices were evaluated. The orifice geometries included:

- Round holes (Module 1);
- 4:1 aspect ratio slots oriented at various angles with respect to the mainstream flow direction (Modules 3, 4, 5, 6, and 7); and
- 8:1 aspect ratio slots oriented at 45° (Module 2).

All modules were 6.51-inch (165 mm) long, with the center of the orifice row placed at one radius from the edge. The orifice area for each module at the design J value was kept constant. As a result, the dimensions of a given orifice varied as a function of the value of J. By way of illustration, schematics are provided in Figures 1 through 3 for Modules 1, 2, and 5. While results were obtained and documented for all the configurations, space constrictions in the present paper limit the presentation of results to the hole and 45° slot configurations. These results, however, are adequate for illustrating the conclusions for the overall study.

Mixing was examined by recording the mean temperature distribution in and downstream of the plane in which cold jets were introduced into a heated mainstream. The mainstream flow entering the modules was heated to the highest temperature (212°F) compatible with the upper temperature limits of the Plexiglass. The jets were introduced at room temperature (72°F).

The operating conditions for the non-reacting experiments are presented in Table 1. Reference velocity, defined as the velocity at the inlet to the mixer section and calculated based on the mainstream temperature and pressure, was 34.5 f/s (10.5 m/s). The actual discharge coefficient and momentum flux ratio for each case was determined by measuring the jet pressure drop.

A 12-inch long, 0.125-inch Type K thermocouple probe was used to measure temperature in and downstream of the jet injection. The thermocouple was held in a fixed position while the test stand was traversed in the X, Y, and Z directions. Temperature was measured at 50 points in a quarter sector of the modules. Figures 4a and 4b show the measurement points and the axial measurement planes respectively. The five planes examined experimentally were located between Z/R = 0.08, and

Table 1. Operating Conditions for Parametric Studies

T_{main} (°F)	T_{jet} (°F)	P (psia)	V_{main} (fps)	M_{main} (pps)	Mass Ratio, MR	Density Ratio, DR
212	74	14.7	34.5	0.10	2.2	1.26

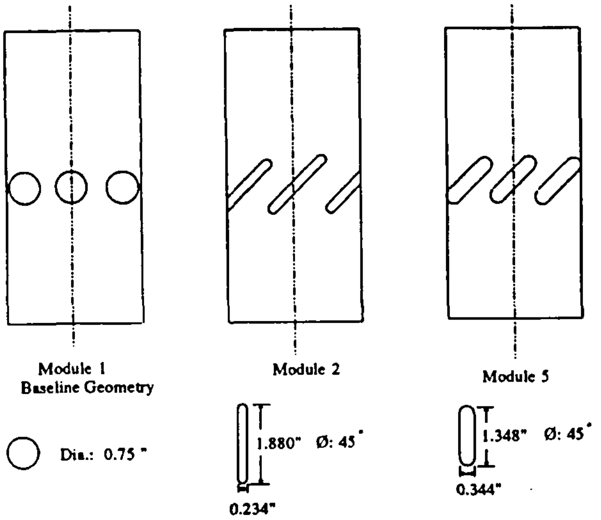


Figure 1. Schematic of Modules for J = 25

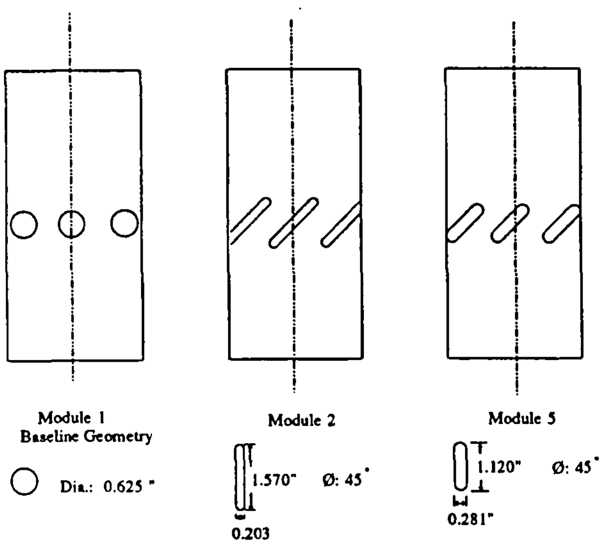


Figure 2. Schematic of Modules for J = 52

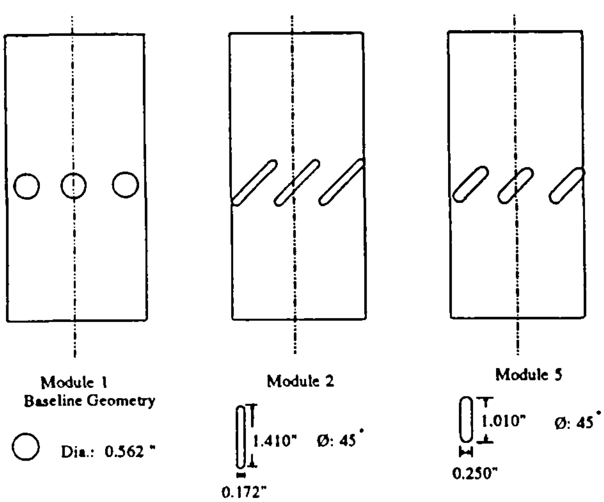


Figure 3. Schematic of Modules for J = 80

Z/R = 1.0 where Z is measured from the leading edge of the orifices (i.e., Z/R = 0.0). The axial location (Z/R) of the trailing edge and the blockage of each module is presented in Table 2. Temperature distributions were recorded using a Fluke temperature readout (Model 2160A), and the mainstream and jet temperatures were monitored using a Beckman temperature indicator (Model 500T).

EXPERIMENTAL FACILITY

An atmospheric test facility located at the UCI Combustion Laboratory was used to conduct the experiments. Both high air flow rates and preheat capability were provided. The house air was filtered and regulated before branching into two isolated main and jet circuits. The jet circuit incorporated four independently metered flow legs. The main circuit consisted of a coarse and fine leg which provided a total of 150 SCFM for the mainstream flow. Each leg was regulated independently to eliminate the effects of pressure fluctuations. All circuits were metered by sonic venturies. The mainstream air was heated to 200°F by a 20 Kw air preheater (Watlow, P/N 86036-2). The outlet temperature was controlled by a heater controller (Watlow, Series 800).

Figure 5 shows a schematic of the test facility. The mainstream air, metered and heated, passed through a 2-inch insulated carbon-steel pipe to the vertically-mounted test bed. A combination honeycomb/screen provided uniform flow at the inlet to the mixer module. A 5-foot long section of 2-inch flexible tubing was provided immediately upstream of the test setup to facilitate traversing the experiment in the X, Y, and Z directions. The test stand was traversed manually, and a Mitutoya Model PM-331 digital traverse readout was used to fix and document the probe sampling coordinates.

The 3-inch mixer section was positioned inside a concentric Pyrex manifold. The manifold had a 5.5-inch (140 mm) outside diameter with a wall thickness of 0.125-inches (3.18 mm). The jet manifold incorporated four openings on top and four on the bottom, each 90° apart, and placed 1-inch from the edges. Four discrete jets were supplied at right angles to the manifold through the bottom openings. Two of the openings on the top were used to measure the manifold temperature and pressure, and the other two were blocked. Each jet circuit was metered individually, and equal lengths of silicone tubing between the flow control panel and the test section were used to provide symmetric flow conditions at the inlet to the manifold. A 1-inch thick, doughnut shaped honeycomb section installed upstream of the orifices, provide uniform flow at the injection point.

ANALYSIS

To meet the goal of the present study, an analysis procedure was established to quantify the mixing uniformity and NO formation characteristics of a module based on the non-reacting temperature measurements.

Mixing Performance

To compare the mixing characteristics of different modules, the temperature measurements were normalized by defining the mixture fraction (f) at each point as follows:

$$f = \frac{T_{measured} - T_{jet}}{T_{main} - T_{jet}}$$

Table 2. Axial Location (Z/R) of Trailing Edge, and Blockage

Module	Holes/ Slots	Aspect Ratio	Angle	Trailing Edge(1) J=25	J=52	J=80	Blockage(2) J=25	J=52	J=80
1	Hole	---	--	0.50	0.42	0.37	0.64	0.53	0.48
2	Slots	8:1	45°	0.93	0.78	0.70	1.19	0.99	0.89
3	Slots	4:1	45°	0.70	0.58	0.53	0.90	0.74	0.67

1. (Axial Projection)/(Radius of Mixing Module)
2. (Circumferential Projection)/(Spacing Between Orifice Centers)

A value of $f = 1.0$ corresponds to the mainstream temperature, while $f = 0$ corresponds to pure jet flow. Complete mixing occurs when the integrated value of f across a given plane yields the equilibrium value which is nearly equal to the ratio of the upstream flow to the total flow. Note, $f = 1 - \theta$ where θ has been used in other studies (e.g., Holdeman, 1993).

To quantify the mixing effectiveness of each module, an area-weighted standard deviation parameter ("Mixing Uniformity") was defined as follows for each Z/R plane:

$$\text{Mixture Uniformity} = \sqrt{\frac{1}{A}\sum_{i=1}^{n} a_i\,(f_i - f_{equil})^2}$$

where $A = \Sigma a_i$, f_i is the mixture fraction calculated at each node, and f_{equil} is the equilibrium mixture fraction defined as:

$$f_{equil} = \frac{T_{equil} - T_{jet}}{T_{main} - T_{jet}}$$

Complete mixing is achieved when the mixture uniformity parameter across a given plane reaches zero.

NO Formation Potential

To establish the NO formation potential of the mixer modules based on the results of the non-reacting studies, a computational method was developed that analyzes the NO formation characteristics of each module using the following procedure:

- Mean temperature measurements in each plane are input to the model along with the jet-to-mainstream mass ratio.
- The spatial distribution of the mixture fraction (f) is computed in a quarter section of each plane by interpolating between the measured temperatures.
- Through interpolation between Z/R = 0.08 to 1.0 (and extrapolation to Z/R = 0.0), the spatial distribution of f is then calculated for one hundred, equally spaced planes from Z/R = 0.0 to 1.0.
- Representative rich zone conditions under aeroengine operation are assumed for the mainstream composition (i.e., products of combustion at an equivalence ratio of 1.6 and an adiabatic temperature of 3600°F) and the temperature of the air jets (i.e., 1250°F).
- An equivalence ratio is then calculated for every point in the computational domain.
- Based on the calculated equivalence ratio and the residence time for each plane, the local temperature, and NO and CO concentrations are calculated by the SENKIN chemical kinetic code (Lutz, Kee, and Miller, 1990). In addition, the spatial distribution of NO production rate and the accumulated NO formed from plane to plane is calculated.
- The results are plotted as mixture fraction, mole fractions of NO and CO, NO production and CO depletion, reacting temperature distribution, and equivalence ratio for each of the five planes within the computational domain.

RESULTS AND DISCUSSION

The influence of geometry and flow conditions on overall mixing has been discussed elsewhere (Hatch, et al., 1992a). This paper addresses the relationship of mixing to the formation of NO. While a myriad of data were acquired for six different orifice geometries, the salient results can be effectively covered by considering the following three modules: Round holes (Module 1), and 45° slanted slots with either 8:1 (Module 2) or 4:1 (Module 5) aspect ratios.

MODULE 1--Baseline Geometry (holes)

In Figures 6, 7, and 8, the equivalence ratio and local NO production rate for the baseline geometry (Module 1) are presented for the three momentum flux ratios: J = 26.7, 55.4, and 84.2 (cases J25MOD1, J52MOD1, and J80MOD1 respectively).*

* The actual (measured) value of J (e.g., "26.7") is presented for each case; the code "J25MOD1" denotes the design J (25) and the configuration (Module 1).

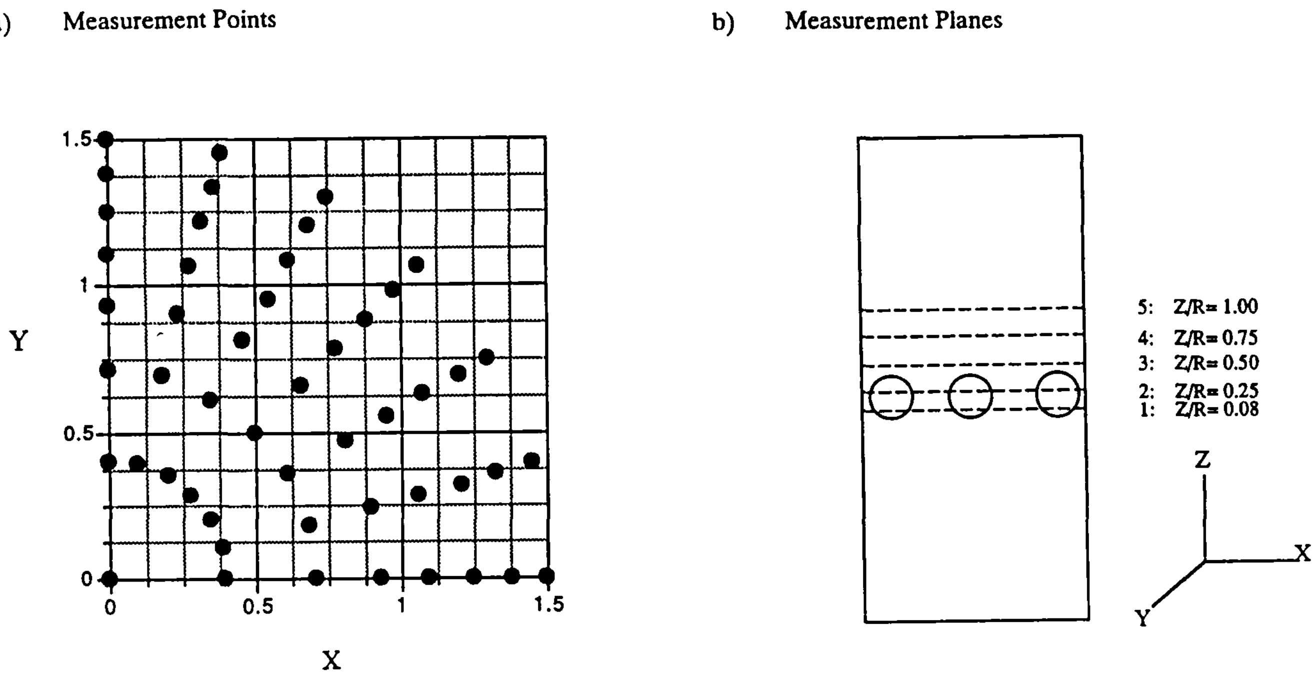


Figure 4. Measurement Locations

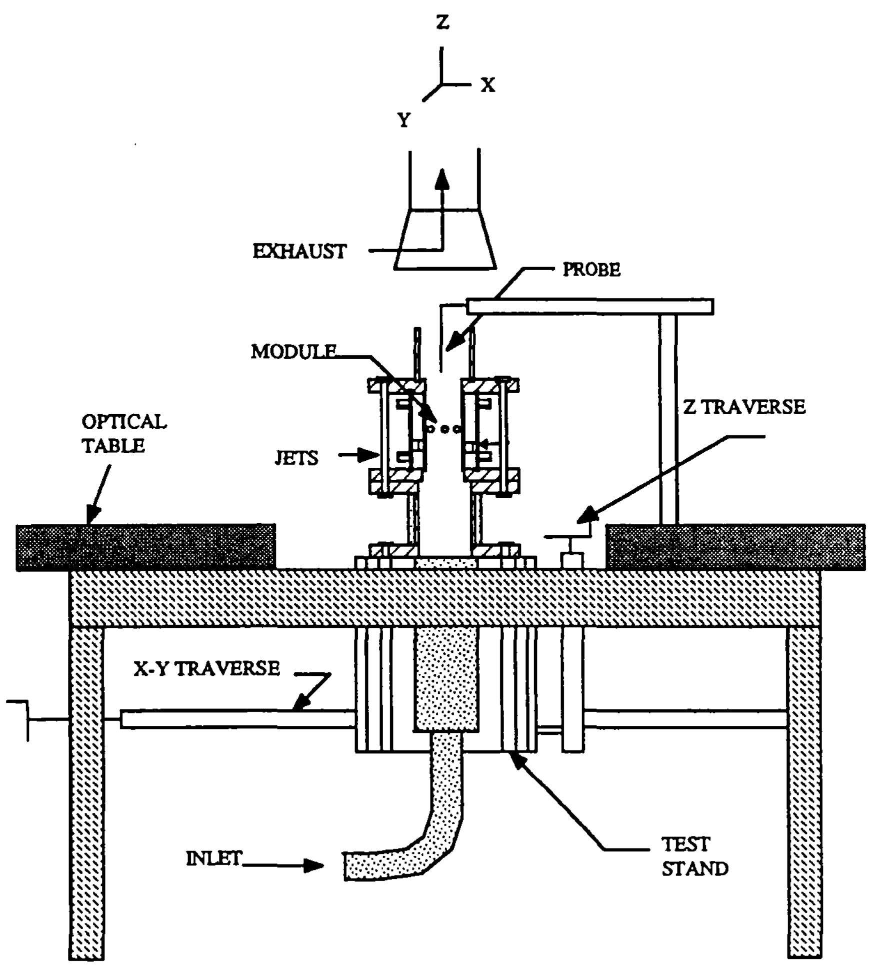
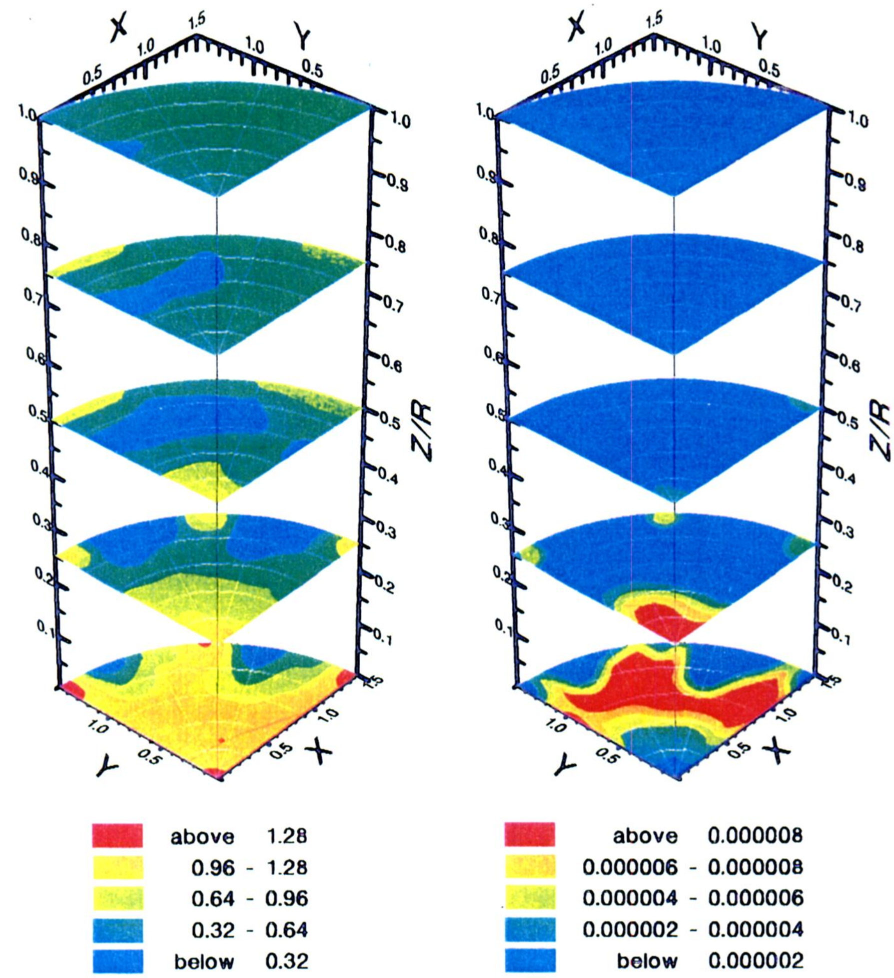


Figure 5. Schematic of Facility



a) Equivalence Ratio

b) NO Formation Rate [g/sec]

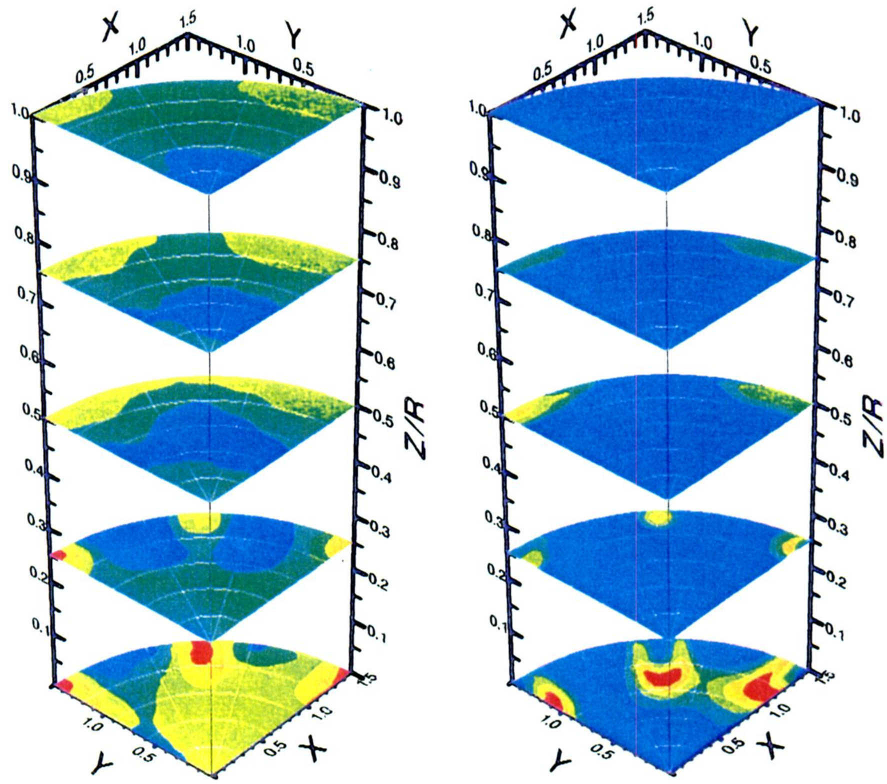
Figure 6. Equivalence Ratio and NO Production (J25MOD1)
Baseline 8-Hole, J=26.7

The color scale bars of Figure 6 apply as well to Figures 7 and 8. The center of the orifices is positioned on the Z/R = 0.0 plane at 22.5° and 67.5°. Note that the data, in general, are not symmetric. Although the holes are symmetrically distributed circumferentially, variations in discharge coefficients of the individual jets due to manufacturing and/or experimental errors such as probe perturbation give rise to the observed asymmetries.

For J = 26.7 (J25MOD1), the majority of NO is produced in the planes between Z/R = 0.0 and 0.5 (Figure 6). At the first axial location (Z/R = 0.0), high concentrations of NO are produced in the shear layer formed between the jets and the mainstream where a large near-stoichiometric region is formed. At Z/R = 0.25, the near-stoichiometric region is concentrated at the center of the module where the NO production is again elevated. Farther downstream, relatively small amounts of NO are produced.

For J = 55.4 (J52MOD1), the near-stoichiometric domain in the first axial location is located in a small region between the jets (Figure 7). The main portion of the flowfield is at equivalence ratios below 1.0 due to a further penetration and enhanced mixing of the jets. The highest rate of NO production again corresponds to the near-stoichiometric region. Further downstream, NO production occurs primarily along the module walls.

A similar pattern of NO production is observed (Figure 8) for J = 84.2 (J80MOD1). However, the production rate of NO for J = 84.2 is lower in the injection plane, and higher downstream in the wall region where mixing is limited and high temperatures persist. Compared to the injection plane, however, the rate of production is relatively low.



a) Equivalence Ratio

b) NO Formation Rate [g/sec]

Figure 7. Equivalence Ratio and NO Production (J52MOD1)
Baseline 8-Hole, J=55.4

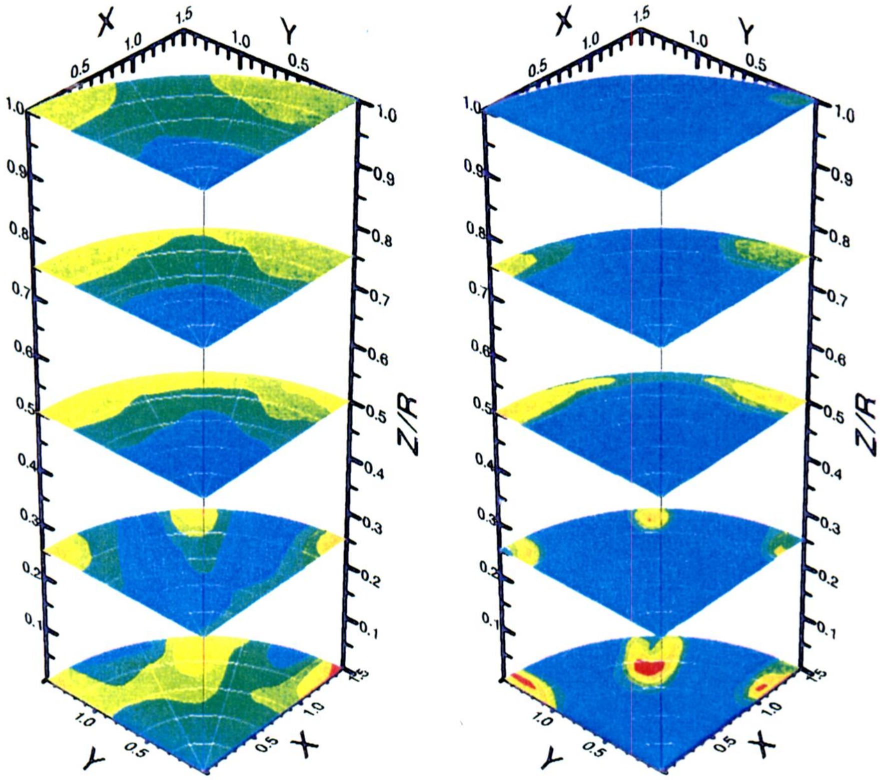
The NO production plots for the baseline modules suggest that the majority of NO is produced early in the mixing process. To explore this further, the plots of Figure 9 are presented. Here, the axial variation in mixing uniformity, NO Production Rate, and Accumulated NO have been plotted. It can be seen that, initially, the rate of NO production is highest for J = 26.7 (Figure 9b). This initial surge of NO production dominates the accumulated NO (Figure 9c). As J is increased, the jets penetrate farther and mixing at the first axial location (Z/R = 0.0) improves. The mixing uniformity plot (Figure 9a) reflects this, showing improvement in mixing between $0.0 < Z/R < 0.2$ as J is increased (mixing improves as the mixing uniformity parameter decreases). The early production of NO is suppressed and the accumulated NO is sharply decreased. The following observations are noteworthy:

- If overall mixing is defined as that configuration and/or condition that minimizes the mixing uniformity at Z/R = 1.0, then the best overall mixing for the present set of data occurs for J = 26.7 (J25MOD1). Note, however, that the NO production resulting from this mixer is the highest of the three flux ratios considered. Hence, the best overall mixer is not necessarily the most effective mixer to minimize NO emission.

- At Z/R = 1.0, the NO production rate is non-zero for the elevated momentum flux ratios of J = 55.4 and 84.2. While the production rate for J = 55.4 is approaching zero, the slope of the accumulated NO for J = 84.2 is positive.

- For Module 1, an increase in the momentum flux ratio results in enhanced initial mixing and lower production of NO. At the highest value of J (84.2), the increase in early mixing is offset by a failure to mix effectively in the wall region. Hence, the value of J = 55.4 is the most attractive of the three values considered. The optimum momentum flux ratio is likely near to, but less than J = 55.4. Hence, under-penetration of the jets results in inadequate initial mixing, and over-penetration results in inadequate mixing in the downstream wall region.

- Over-penetration can have an additional detrimental effect not considered in the present model. At the elevated momentum flux ratios, a high penetration of the jets can produce a backflow on the centerline. This will promote formation of nitric oxide upstream of the jet injection plane and adversely affect, as a result, the emission performance of the mixer.



a) Equivalence Ratio

b) NO Formation Rate [g/sec]

Figure 8. Equivalence Ratio and NO Production (J80MOD1)
Baseline, 8-Hole, J=84.2

MODULE 5--(4:1 slots; 45°)

The mixture uniformity, NO production rate, and accumulated NO are presented in Figure 10 for the 45°, 4:1 aspect ratio slanted slot configurations: J25MOD5 (J = 30.2), J52MOD5 (J = 57.7), and J80MOD5 (J = 93.0). Contour plots for equivalence ratio and NO production potential are shown in Hatch, et al., 1992b.

As with the baseline module, the more effective early mixing (J80MOD5; J = 93.0) leads to the lowest NO production rate at the plane of injection. Also witnessed here is the fact that the accumulated NO at Z/R = 1.0 is a combination of the early NO production and the extent of mixing in the wall region downstream of the injection plane.

An evaluation of the accumulated NO plot illustrates the trade-off for this configuration between enhanced early mixing (J80MOD5; J = 93.0), and enhanced wall region mixing (J52MOD5; J = 57.7). At Z/R = 1.0, the value of NO and slope suggest that a momentum flux ratio between 57.7 and 93.0 would likely be optimum.

MODULE 2--(8:1 slots; 45°)

The results for the 8:1 45° slanted slot module are presented in Figure 11 for the following configurations: J25MOD2 (J = 28.1), J52MOD2 (J = 50.9), and J80MOD2 (J = 88.9). Noteworthy here is the effect of early mixing on NO production. For example, the J = 88.9 case (J80MOD2) is the most effective early mixer, but (in contrast to the baseline and 4:1 aspect ratio configurations) is highest in the production of NO within the jet injection plane. To understand, it is necessary to recall that the slanted slot introduces the jet air over a relatively long axial distance. The 8:1 aspect ratio configuration introduces the air over the longest distance (refer to Figures 1, 2, and 3) with the trailing edge near Z/R = 1.0 (refer to Table 2), the furthermost downstream location of interest in the current study. For J = 88.9 (J80MOD2), while the momentum flux ratio is the most effective in early mixing, the amount of air injected is just sufficient to bring a substantial mass of fluid to near-stoichiometric mixture conditions.

Overall, the 4:1 aspect ratio and straight hole configurations are more effective mixers with respect to NO production that the 8:1 aspect ratio configuration, producing a factor of 2 less emission.

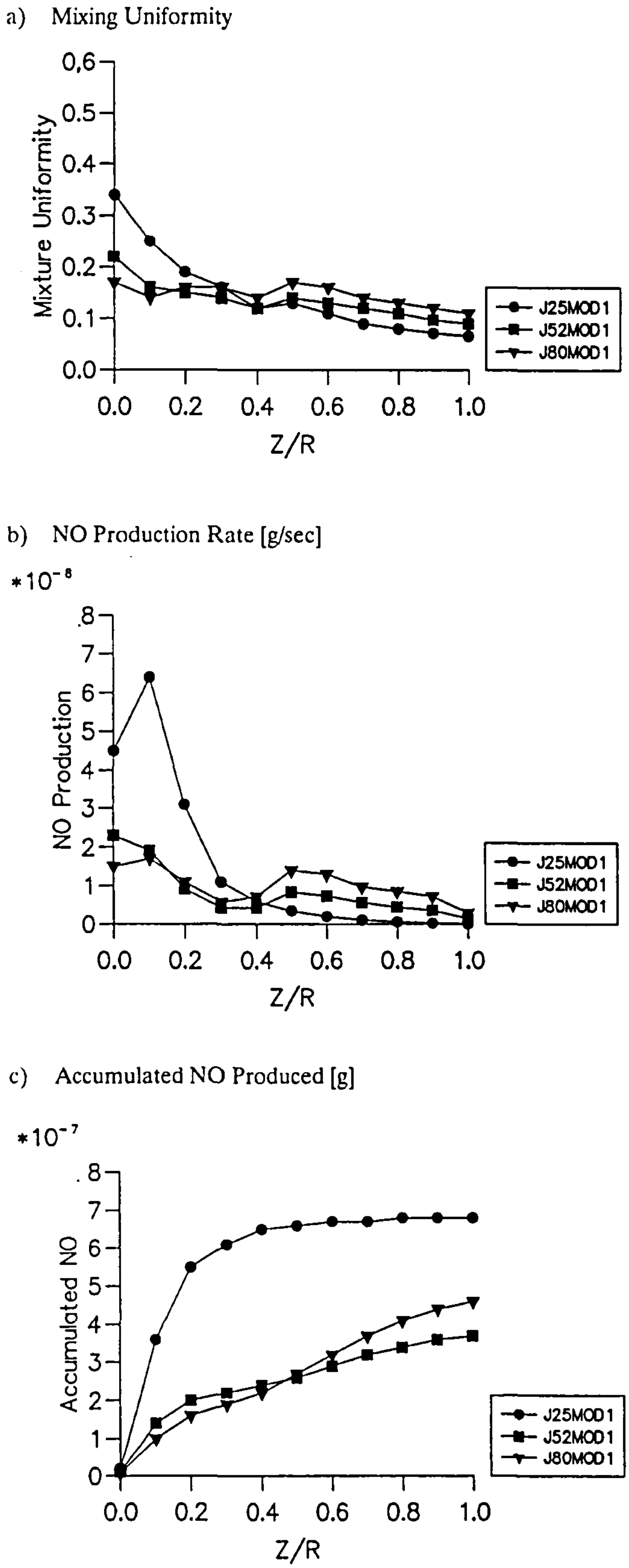


Figure 9. Module 1--Baseline 8-Hole

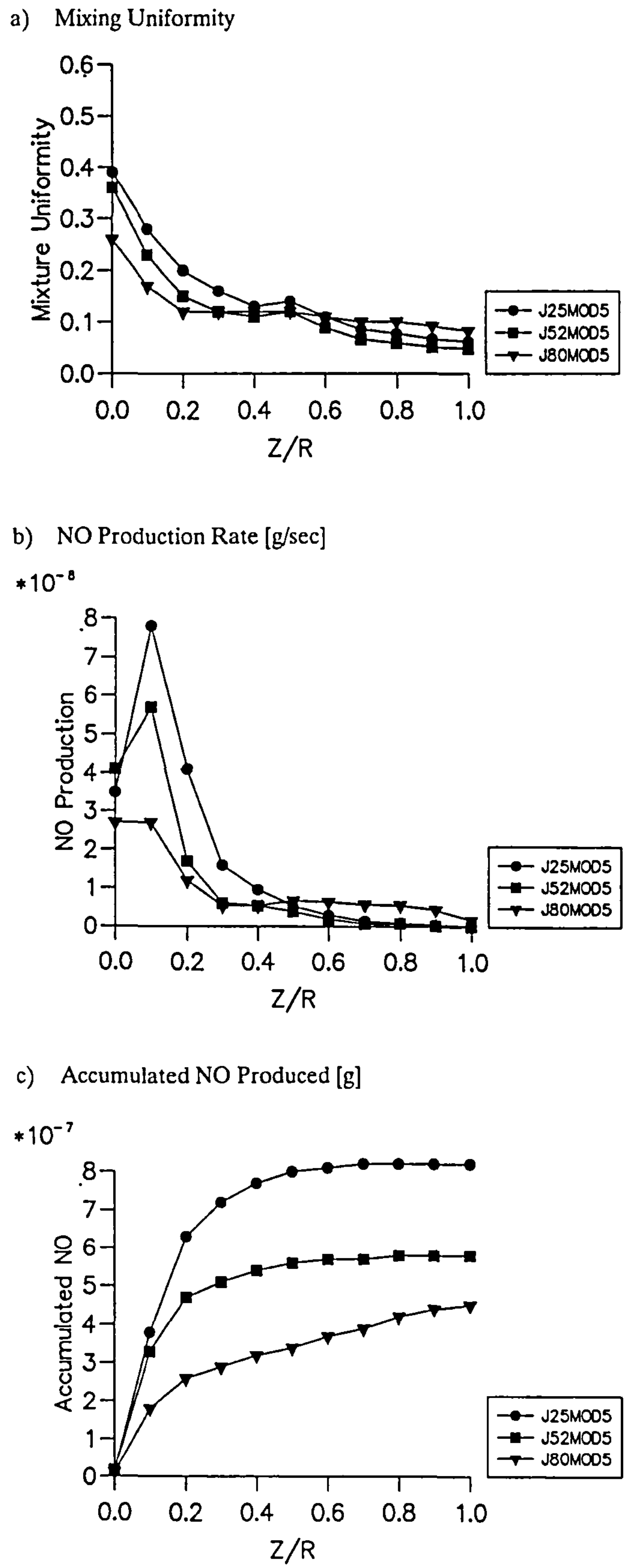


Figure 10. Module 5--45° 4:1 Aspect Ratio Slanted Slots

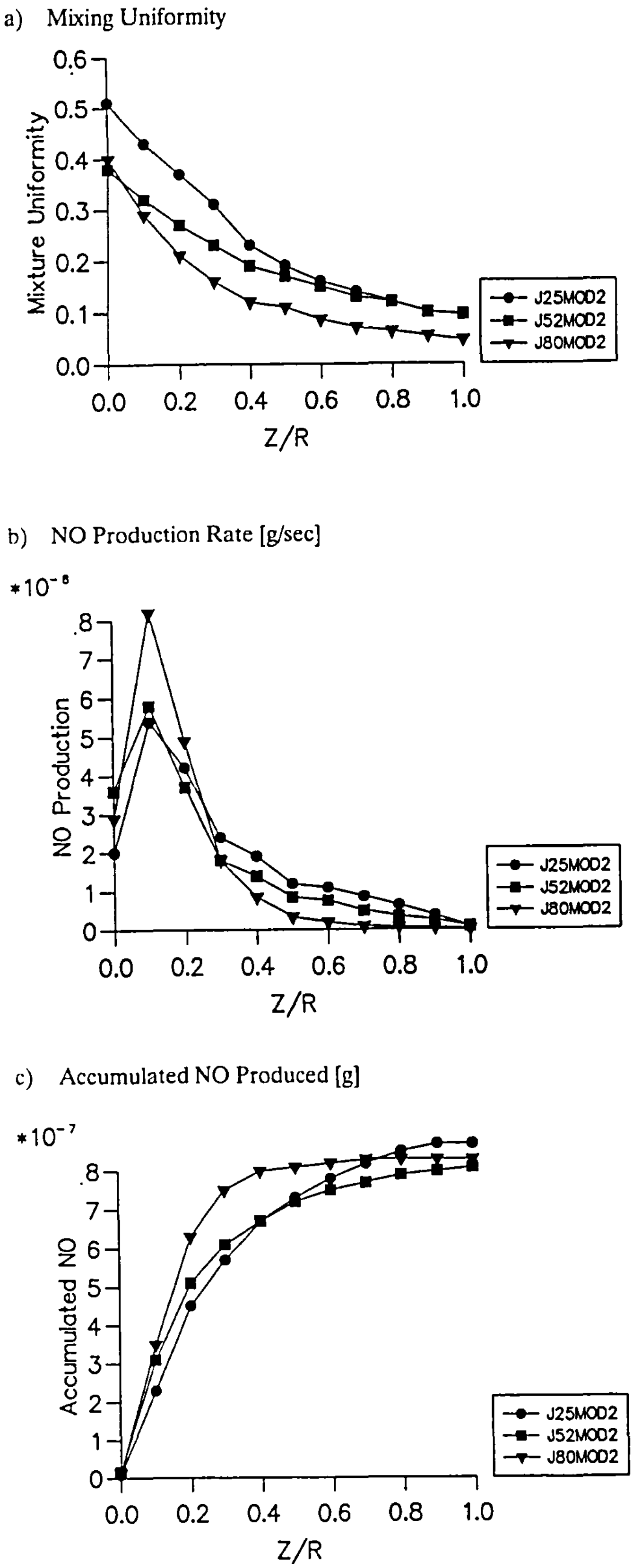


Figure 11. Module 2--45° 8:1 Aspect Ratio Slanted Slots

CONCLUSIONS

1. The majority of nitric oxide is formed early, within the jet injection plane. As a result, the mixing processes in this region are critical to the overall emission performance of the mixer.
2. Rapid early mixing does not necessarily lead to a minimum early production rate of nitric oxide.
3. The minimization of NO production from a quick mixer requires an optimization between two competing tradeoffs: Effective mixing in the plane of injection, and effective mixing in the wall regions downstream of the plane of injection. The present results demonstrate that the momentum flux ratio and orifice geometry are critical parameters in optimizing this trade-off.
4. The present results suggest that (1) further study will not necessarily lead to a universal "rule-of-thumb" for the combination of orifice geometry and momentum flux ratio that minimizes the production of NO, and (2) the determination of the optimal combination will likely require an assessment for the specific application (e.g., operating conditions, geometrical constraints, mass ratio).
5. For the range of momentum flux ratios and orifice geometries evaluated in the present case, the holes and 45° 4:1 slanted slots at a momentum flux ratio of approximately J = 52 yield the best mixers from a NO production perspective. Noteworthy is that the slot has not been optimized for this momentum flux ratio. Once optimized, a slot geometry may provide more effective than the hole.

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13. ABSTRACT ***(Maximum 200 words)***

Staged combustion, such as Rich-Burn/Quick-Mix/Lean-Burn (RQL), is a viable strategy to meet nitric oxide (NO) emission goals for both stationary and propulsion gas turbine engines. A critical element of the design is the quick mixer section where the potential for NO production is high. While numerical calculations of the quick mixer under reacting conditions have been conducted, the hostile environment and lack of appropriate diagnostics have, to date, precluded experimental probing of the reacting case. As an alternative to understanding the effect of geometry and flow variations on the production of NO in the quick mixer, the present paper presents (1) a series of non-reacting parametric studies, and (2) a computational method to extrapolate the results of the non-reacting experiments to reacting conditions. The results show that the rate of NO production is highest in the immediate vicinity of the injection plane. For a given momentum flux ratio between the jets and mainstream, the most effective mixing geometry is that which mixes effectively in both (1) the plane of injection, and (2) the wall regions downstream of the plane of injection. The tailoring of the mixing is key to minimize the NO formed. As a result, the best overall mixer with respect to the minimization of NO production may depend on the system specific characteristics of the particular application.

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